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(54) Abstract Title: **A method and apparatus for determining the lateral speed of a motor vehicle**

(57) An apparatus for determining lateral speed of an automotive vehicle 10 includes a vehicle speed sensor 20, a roll rate sensor 34, a yaw rate sensor 28, a lateral acceleration sensor 32, and a longitudinal acceleration sensor 36. A controller 26 is coupled to the sensors and determines a steady state pitch angle and a steady state roll angle as a function of the lateral acceleration signal, the longitudinal acceleration signal, the yaw rate signal, and the vehicle speed signal. The controller determines a sliding index as a function of the steady state pitch signal, the steady state roll angle, and the roll rate signal. The controller 26 determines lateral velocity as a function of the sliding index and controls the vehicle lateral motion based on the estimated lateral speed.

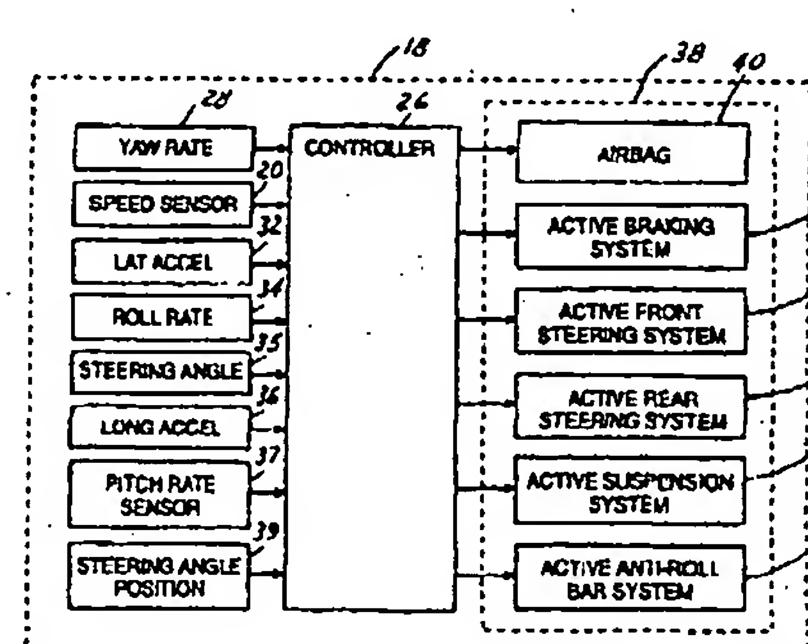

FIG. 4

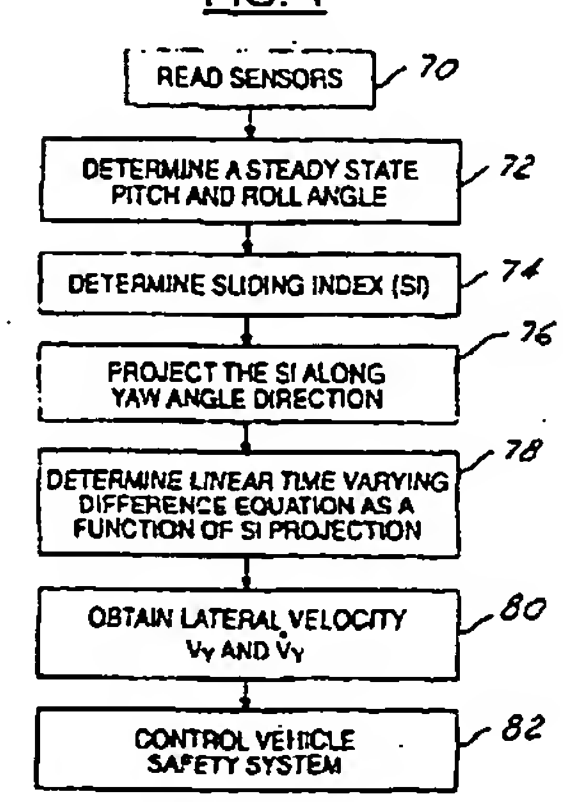

FIG. 5

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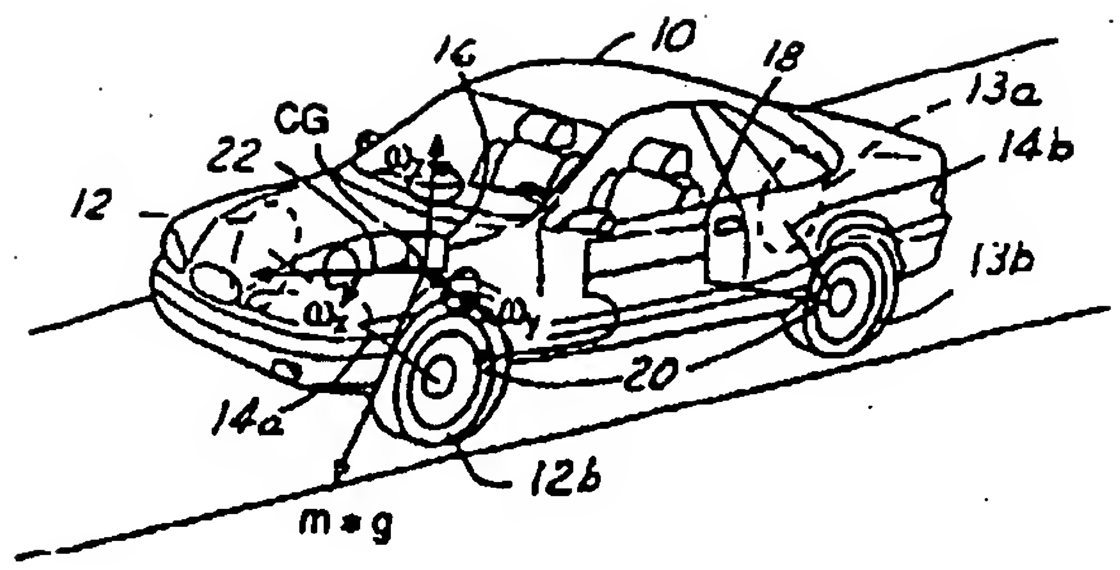
10
16
18
13a
14b
CG
22
12
13b
20
14a
12b
m*g

FIG. 1

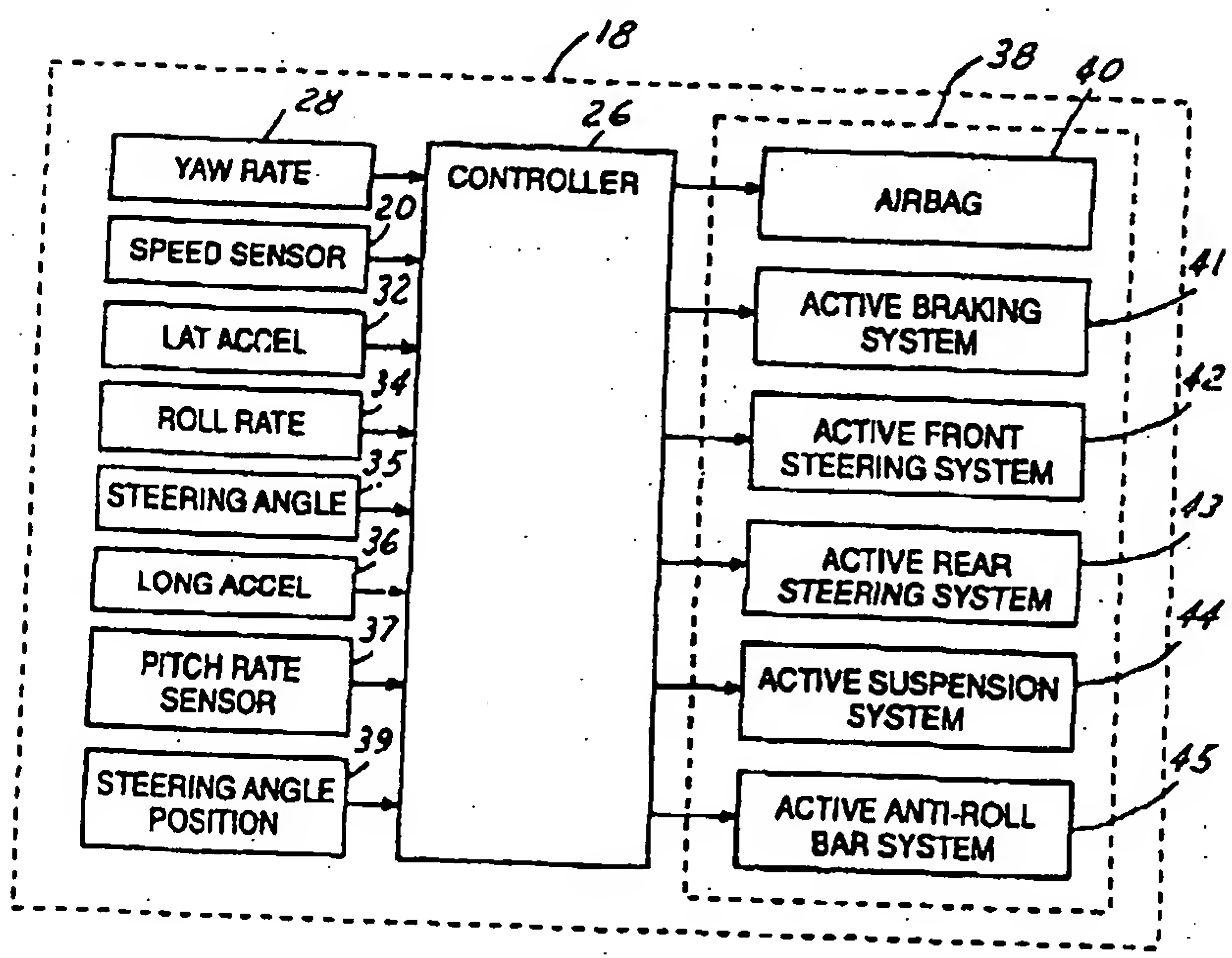
18
38
40
28
26
YAW RATE
CONTROLLER
AIRBAG
20
SPEED SENSOR
32
LAT ACCEL
ACTIVE BRAKING SYSTEM
41
34
ROLL RATE
ACTIVE FRONT STEERING SYSTEM
42
35
STEERING ANGLE
36
LONG ACCEL
ACTIVE REAR STEERING SYSTEM
43
37
PITCH RATE SENSOR
ACTIVE SUSPENSION SYSTEM
44
39
STEERING ANGLE POSITION
ACTIVE ANTI-ROLL BAR SYSTEM
45

FIG. 4

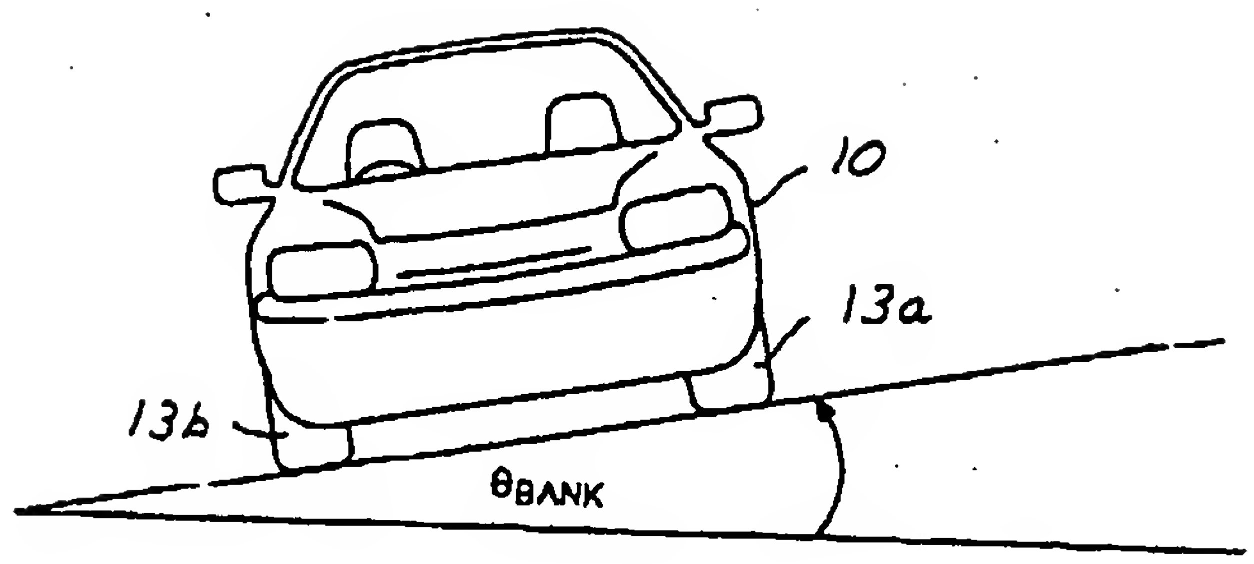

FIG. 2

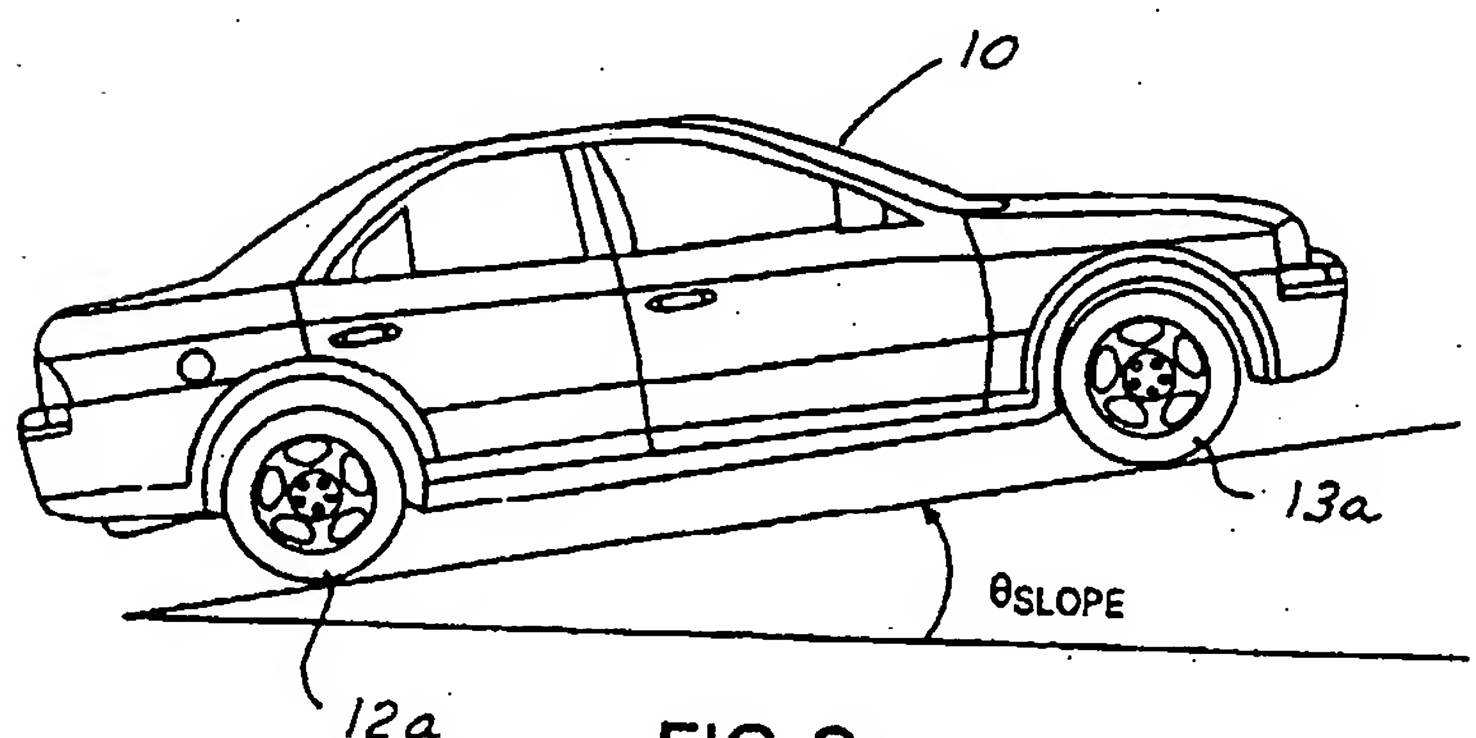

FIG. 3

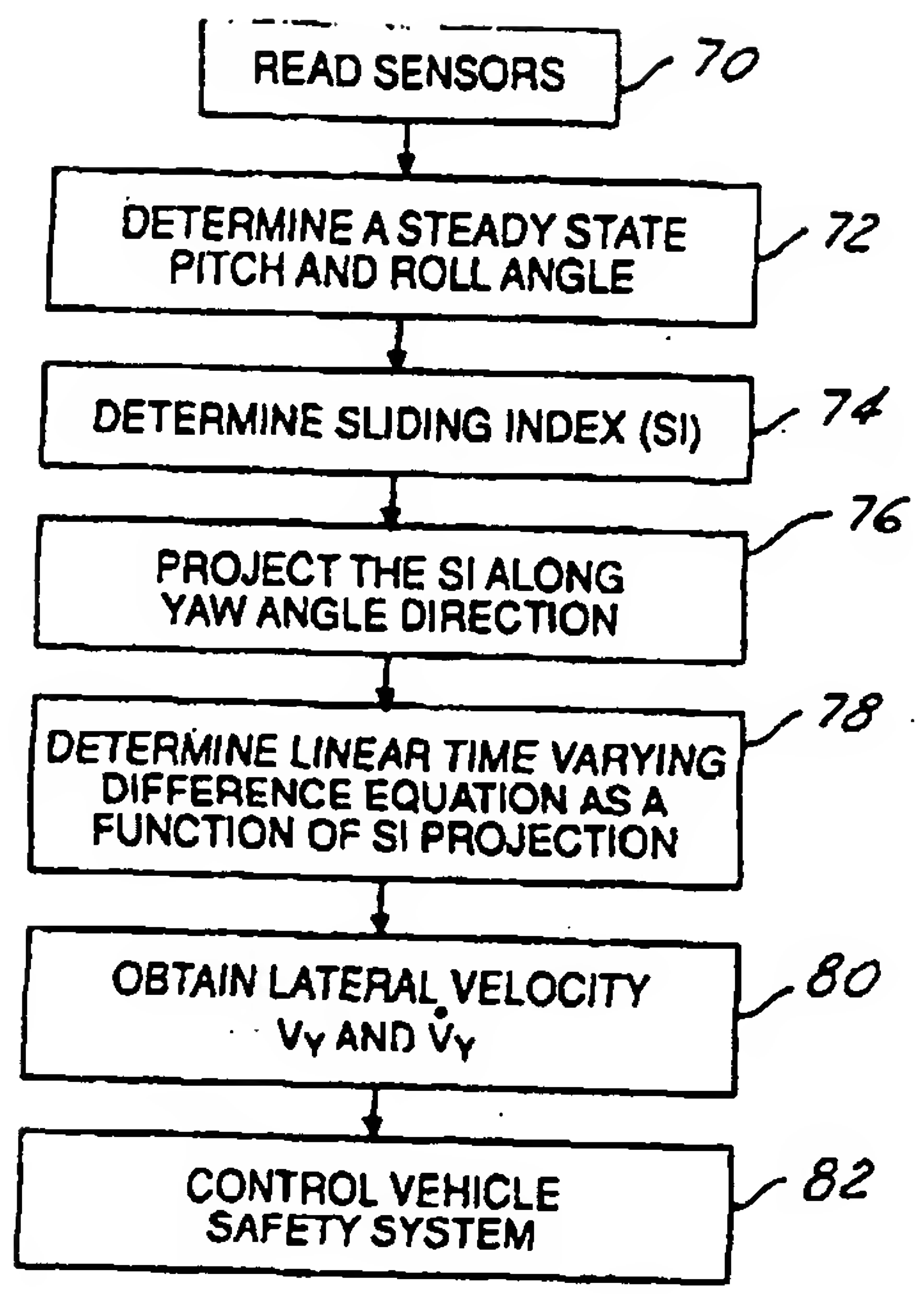
READ SENSORS
70
DETERMINE A STEADY STATE PITCH AND ROLL ANGLE
72
DETERMINE SLIDING INDEX (SI)
74
PROJECT THE SI ALONG YAW ANGLE DIRECTION
76
DETERMINE LINEAR TIME VARYING DIFFERENCE EQUATION AS A FUNCTION OF SI PROJECTION
78
OBTAIN LATERAL VELOCITY V_Y AND $\dot{V}_Y$
80
CONTROL VEHICLE SAFETY SYSTEM
82

FIG. 5

A METHOD AND APPARATUS FOR DETERMINING LATERAL VELOCITY OF A MOTOR VEHICLE

The present invention relates generally to determining the dynamic state of an automotive vehicle, and more particularly, to a method and apparatus for determining lateral velocity of an automotive vehicle.

It is a well-known practice to control various operating dynamics of a motor vehicle to achieve active safety, using yaw and roll stability control systems. The effective operation of the various safety control devices requires high-accuracy and fast-response-time of the operating state of the motor vehicle, regarding the various road conditions and driving conditions. One important operating state used in such systems is the vehicle lateral velocity.

As a vehicle is driven, it may slide with respect to the road surface along the vehicle lateral axis, especially when it is driven on a low friction (low mu) road surface. This sliding can be quantitatively estimated using the lateral velocity of the centre of gravity of the vehicle, projected on the lateral direction of the vehicle. The lateral velocity combined with other vehicle dynamic variables, such as longitudinal velocity and yaw rate, may be used for vehicle attitude sensing. The vehicle attitude may be used to generate control commands for vehicle yaw and roll stability control systems. Lateral velocity may be directly measured by sensors such as optical sensors or global positioning system (GPS) sensors. However, those sensors are very costly for the current vehicle dynamics controls. Hence it is desirable to use other available sensor signals to estimate the vehicle lateral velocity.

Many known systems rely upon basic assumptions regarding conditions such as driving on a flat surface (no

pitch or bank angle), or on a high mu surface, or with a small vehicle attitude change. One example of such a system is found in U.S. Patent 5,742,919, which provides a method to estimate the lateral velocity. The disclosed method is accurate only when the road is flat, the road surface has high mu, and vehicle has very small roll motion.

Another known method uses a lateral acceleration sensor signal to construct the time derivative of the vehicle lateral velocity by taking away the product of the yaw rate and the vehicle longitudinal velocity. Since the road condition (for example, the road bank and slope), the dynamic roll, and the dynamic pitch attitude of the vehicle will generate an extra component in the lateral acceleration, this method fails to detect accurate lateral velocity on banked/slope road or when the vehicle body has significant attitude changes. For example, an aggressive driver steering input may cause large roll attitude variation of the vehicle; during off-road driving, the large road bank and slope will be experienced through vehicle attitude changes. A vehicle with large lateral acceleration manoeuvres could achieve 6 degrees of relative roll angle between the vehicle body and a level road surface.

If such a vehicle is driven at 45 mph off camber on a 10 degree banked road, the lateral acceleration sensor reading will be increased by 2.7 m/s^2 solely due to gravity. Hence, neglecting the road bank and the vehicle roll information could introduce an error of 2.7 m/s per second. That is, a 2 second manoeuvre in this case will end up with around 5.4 m/s lateral velocity error which is more than 27% of the vehicle speed of 45 mph.

It is an object of this invention to provide an apparatus and method for providing a robust determination of lateral velocity that is reliable on roads having banks,

slopes, various surface mu's (μ) and when the vehicle is operating under changing dynamic conditions.

According to a first aspect of the invention there is provided a apparatus for determining lateral velocity of a motor vehicle comprising a vehicle speed sensor for generating a vehicle speed signal, a roll rate sensor for generating a roll rate signal, a yaw rate sensor for generating a yaw rate signal, a lateral acceleration sensor for generating a lateral acceleration signal, a longitudinal acceleration sensor for generating a longitudinal acceleration signal and a controller coupled to the sensors for determining a steady state pitch angle and a steady state roll angle as a function of the lateral acceleration signal, the longitudinal acceleration signal, the yaw rate signal, and the vehicle speed signal, determining a sliding index as a function of the steady state pitch angle, the steady state roll angle and the roll rate signal, and determining a lateral velocity as a function of the sliding index.

The apparatus may further comprise a safety system coupled to the controller, the safety system operating in response to the lateral velocity.

The safety system may comprise a yaw control system or may comprise a roll stability control system.

The controller may determine a lateral velocity and a lateral velocity derivative as a function of the sliding index.

According to a second aspect of the invention there is provided a method of controlling a vehicle comprising measuring a vehicle speed, measuring a roll rate of the vehicle, measuring a yaw rate of the vehicle, measuring a lateral acceleration of the vehicle, measuring a

longitudinal acceleration of the vehicle, determining a lateral velocity as a function of the longitudinal acceleration, the vehicle speed, the lateral acceleration, the yaw rate and the roll rate and controlling a safety system in response to the lateral velocity.

The method may further comprise determining a steady state pitch angle as a function of the longitudinal acceleration and the vehicle speed.

The method may further comprise determining a steady state roll angle as a function of the lateral acceleration, the yaw rate, and the vehicle speed.

The method may further comprise determining a sliding index as a function of the steady state pitch angle, the steady state roll angle and the roll rate.

The method may further comprise determining a lateral velocity derivative as a function of the sliding index.

The safety system may comprise a yaw control system or may comprise a rollover control system.

The method may further comprise generating a differential equation obeyed by the lateral velocity and its derivative by using the sliding index.

The differential equation may be derived by projecting the sliding index along a yaw angle direction.

The step of projecting the sliding index along the yaw angle directions may be accomplished using an anti-drift-integration filter.

The method may further comprise computing yaw angle through pure integration and 2π congruent mod operation,

such that the accumulated integration error of the real signal is eliminated.

It is an advantage of the present invention that a closed form formula for lateral velocity and a reliable computation provides an estimation of the vehicle lateral velocity. It is a further advantage of the present invention that the estimation of the lateral velocity is accurate regardless of road profile (flat, banked, or graded road surface), road surface condition (low or high mu), and driving conditions (large or small roll/pitch/yaw combined motion).

Other advantages and features of the present invention will become apparent when viewed in light of the detailed description of the preferred embodiment when taken in conjunction with the attached drawings and appended claims.

The invention will now be described by way of example with reference to the accompanying drawing of which:-

Figure 1 is a diagrammatic view of a vehicle with variable vectors and coordinator frames according to the present invention;

Figure 2 is an end view of an automotive vehicle on a bank;

Figure 3 is a side view of a vehicle on a pitch slope;

Figure 4 is a block diagram of a stability system or apparatus according to the present invention; and

Figure 5 is a flow chart of the operation according to a method of the present invention.

In the following figures the same reference numerals will be used to identify the same components. The present invention is preferably used in conjunction with a safety system such as a yaw stability control system or a roll stability control system for an automotive vehicle. However, the present invention may also be used with a deployed safety system device such as airbag. The present

invention will be discussed below in terms of preferred embodiments relating to an automotive vehicle moving in a three-dimensional road terrain.

Referring to Figure 1, an automotive vehicle 10 with a safety system of the present invention is illustrated with various forces and moments acting thereon. Vehicle 10 has front right and front left tyres 12a, 12b and rear right and rear left tyres 13a,13b respectively. The vehicle 10 may also have a number of different types of front steering systems 14a and rear steering systems 14b including having each of the front and rear wheels configured with a respective controllable actuator, the front and rear wheels having a conventional type system in which both of the front wheels are controlled together and both of the rear wheels are controlled together, a system having conventional front steering and independently controllable rear steering for each of the wheels, or vice versa.

Generally, the vehicle has a weight represented as Mg at the centre of gravity of the vehicle, where $g = 9.8\, m/s^2$ and M is the total mass of the vehicle.

As mentioned above, the system may also be used with active/semi-active suspension systems, anti-roll bar or other safety devices deployed or activated upon sensing predetermined dynamic conditions of the vehicle.

The sensing system 16 is coupled to a control system 18. The sensing system 16 preferably uses a standard yaw stability control sensor set (including lateral acceleration sensor, yaw rate sensor, and wheel speed sensor) together with a roll rate sensor and a longitudinal acceleration sensor. The various sensors will be further described below. The wheel speed sensors 20 are mounted at each corner of the vehicle and the rest of the sensors of sensing system 16 are preferably mounted directly on the centre of

gravity of the vehicle body, along the directions x, y and z shown in Figure 1. As those skilled in the art will recognize, the frame from b_1, b_2 and b_3 is called a body frame 22, whose origin is located at the centre of gravity of the car body, with the b_1 corresponding to the longitudinal or x axis pointing forward, b_2 corresponding to the lateral or y axis pointing off the driving side (to the left), and the b_3 corresponding to the vertical or z axis pointing upward.

The angular rates of the car body are denoted about their respective axes as w_x for the roll rate, w_y for the pitch rate and w_z for the yaw rate.

The angular rate sensors and the acceleration sensors are mounted on the vehicle car body along the body frame directions b_1, b_2 and b_3, which are the x - y - z axes of the vehicle's sprung mass.

The longitudinal acceleration sensor is mounted on the car body at the centre of gravity with its sensing direction along b_1-axis, and its output is denoted as a_x. The lateral acceleration sensor is mounted on the car body at the centre of gravity with its sensing direction along b_2-axis, and its output is denoted as a_y.

Referring now to Figure 2, the present invention determines a lateral velocity by compensating a road bank angle θ_{bank} if the vehicle body has small roll attitude with respect to the road surface or otherwise a vehicle roll attitude angle θ_x which is the global roll angle of the vehicle body with respect to the sea level. A steady state roll angle may be used in the determination. Thus, the presence of either road bank or large vehicle roll attitude change will still allow an accurate determination of lateral velocity of the vehicle using the present invention.

Referring now to Figure 3, the present invention determines lateral velocity by compensating a slope or pitch angle θ_{slope} if the vehicle body has small pitch attitude with respect to the road surface, or otherwise a vehicle pitch attitude angle θ_y which is the global pitch angle of the vehicle body with respect to the sea level. A steady state pitch angle may be used in the determination. Thus, the presence of either road pitch or large vehicle pitch attitude will still allow an accurate determination of lateral velocity with the system of the present invention.

Referring now to Figure 4, control system 18 is illustrated in further detail having a controller 26 used for receiving information from a number of sensors which may include a yaw rate sensor 28, a speed sensor 20, a lateral acceleration sensor 32, a roll rate sensor 34, a steering angle sensor (hand wheel position) 35, a longitudinal acceleration sensor 36, a pitch rate sensor 37 and steering angle position sensor 39.

In the preferred embodiment, only two axial rate sensors are used. When two of these axial rates are known, the other may be derived using other commonly available sensors. Preferably, yaw rate and roll rate are used as the axial rate sensors. Although pitch rate sensor 37 is illustrated, it may be eliminated in the preferred embodiment.

In the preferred embodiment, the sensors are located at the centre of gravity of the vehicle. Those skilled in the art will recognize that the sensor may also be located off the centre of gravity and translated equivalently thereto.

Lateral acceleration, roll orientation and speed may be obtained using a global positioning system (GPS). Based upon inputs from the sensors, control circuit 26 may control a safety device 38. Depending on the desired sensitivity of

the system and various other factors, not all the sensors 28-39 may be used in a commercial embodiment. Safety device 38 may control an airbag 40, an active braking system 41, an active front steering system 42, an active rear steering system 43, an active suspension system 44, and an active anti-roll bar system 45, or combinations thereof. Each of the systems 40-44 may have their own controllers for activating each one. As mentioned above, the safety system 38 is preferably at least the active braking system 41.

Roll rate sensor 34 and pitch rate sensor 37 may sense the roll condition of the vehicle based on sensing the height of one or more points on the vehicle relative to the road surface. Sensors that may be used to achieve this include a radar-based proximity sensor, a laser-based proximity sensor and a sonar-based proximity sensor.

Roll rate sensor 34 and pitch rate sensor 37 may also sense the roll condition based on sensing the linear or rotational relative displacement or displacement velocity of one or more of the suspension chassis components. Roll and pitch rate sensors 34,37 may comprise a linear height or travel sensor, a rotary height or travel sensor, a wheel speed sensor used to look for a change in velocity, a steering wheel position sensor, a steering wheel velocity sensor and/or a driver heading command input from an electronic component that may include steer by wire using a hand wheel or joy stick.

The roll rate may also be determined by sensing the force or torque associated with the loading condition of one or more suspension or chassis components. These parameters may be measured by a pressure transducer in an active air suspension, a shock absorber sensor such as a load cell, a strain gauge, a steering system absolute or relative motor load sensor, a steering system hydraulic pressure sensor, a lateral force sensor or sensors, a longitudinal tire force

sensor, a vertical tire force sensor or a tire sidewall torsion sensor.

The roll rate of the vehicle may also be established by one or more of the following: translational or rotational positions, velocities or accelerations of the vehicle. These parameters may me determined by one or more of the following: a roll gyro, the roll rate sensor 34, the yaw rate sensor 28, the lateral acceleration sensor 32, a vertical acceleration sensor, a vehicle longitudinal acceleration sensor, lateral or vertical speed sensor including a wheel-based speed sensor, a radar-based speed sensor, a sonar-based speed sensor, a laser-based speed sensor or an optical-based speed sensor.

Based on the inputs from sensors 28 through 39, controller 26 determines a roll condition and controls any one or more of the safety devices 40-45.

Speed sensor 30 may be one of a variety of speed sensors known to those skilled in the art. For example, a suitable speed sensor may include a sensor at every wheel that is averaged by controller 26. Preferably, the controller translates the wheel speeds into the speed of the vehicle. Yaw rate, steering angle, wheel speed and possibly a slip angle estimate at each wheel may be translated back to the speed of the vehicle at the centre of gravity. Various other algorithms are known to those skilled in the art. Speed may also be obtained from a transmission sensor. For example, if speed is determined while speeding up or braking around a corner, the lowest or highest wheel speed may not be used because of its error.

From a basic dynamics consideration, there are kinematic relationships among the following variables for a moving vehicle: the lateral acceleration a_y, the longitudinal acceleration a_x, the roll rate ω_x, the yaw

rate ω_y, the vehicle reference velocity v_x, the vehicle body roll attitude θ_x, the vehicle body pitch attitude (slope angle) θ_y, the vehicle lateral velocity v_y and the pitch rate ω_y. These kinematic relationships can be expressed through the following nonlinear and differential equations

$$
\begin{aligned}
a_x &= \dot{v}_x - \omega_z v_y - g\sin(\theta_y) \\
a_y &= \dot{v}_y + \omega_z v_x + g\sin(\theta_x)\cos(\theta_y) \\
\dot{\theta}_x &= \omega_x + [\omega_y \sin(\theta_x) + \omega_{z3}\cos(\theta_x)]\tan(\theta_y) \\
\dot{\theta}_y &= \omega_y \cos(\theta_x) - \omega_z \sin(\theta_x)
\end{aligned}
\qquad (1.1)
$$

As mentioned before, the determination of lateral velocity used through the first equation of (1.1) might be expressed as

$$\dot{v}_y = a_y - [\omega_z v_x + g\sin(\theta_x)\cos(\theta_y)]$$

and the existing methods in current literature neglecting the vehicle global pitch and roll attitudes leads to

$$\dot{v}_y \approx a_y - \omega_z v_x$$

Also notice that even though the vehicle global attitudes θ_x and θ_y are available, a careful integration scheme needs to be chosen in order to get v_y through integrating $a_y - [\omega_z v_x + g\sin(\theta_x)\cos(\theta_y)]$. Since v_y could have both high frequency and low frequency components, a simple integration with high-pass filter may not obtain the desired result. This difficulty is because it is hard to distinguish between the integration drifting and the actual low frequency sliding of the vehicle. The present invention obtains an accurate estimation regardless of such difficulties.

In the current vehicular yaw or roll stability control, a_y, a_x, ω_x and ω_y are measured sensor signals, and v_x is known (calculated from the wheel speed sensor signals and the other calculated signals used in yaw stability controls), while θ_x, θ_y, v_y and ω_y are unknown. Hence, computing the vehicle lateral velocity from Equation (1.1) requires solving a set of nonlinear differential equations. The solution to the above nonlinear differential equations can be obtained through solving a single linear but time-varying differential equation. The advantage of solving a linear-time varying differential equation over solving nonlinear differential equations is that the closed-form solution for linear differential equations in general can be found, which is usually impossible for nonlinear differential equations. The closed-form solution directly calculates lateral velocity v_y from the known signals a_y, a_x, ω_x, ω_y and v_x by eliminating the known variables θ_x, θ_y and ω_y. One advantage of this treatment is that potential numerical errors found in integration for θ_x, θ_y and ω_y will be eliminated. Therefore, the system is more robust and reliable.

If a vehicle is driving on a stable condition, the lateral velocity is likely to be close to zero. In this case, the corresponding vehicle roll and pitch attitudes are denoted as θ_{xss} and θ_{yss}, which can be obtained by setting $v_y = 0$ in the first two equations of Equation (1.1).

$$\theta_{yss} = a\sin(\frac{\dot{v}_x - a_x}{g})$$
$$\theta_{xss} = a\sin(\frac{a_y - \omega_z v_x}{g\cos(\theta_{yss})}) \tag{1.2}$$

Notice that Equation (1.2) does not correspond to any real values of the vehicle attitudes if the vehicle has significant sliding motion in the lateral direction, and in this case, the vehicle attitudes obey the following

$$\theta_y = a\sin[\sin(\theta_{yss}) - \omega_z \frac{v_y}{g}]$$
$$\theta_x = a\sin[\frac{a_y - \omega_z v_x}{g\cos(\theta_y)} - \frac{\dot{v}_y}{g\cos(\theta_y)}] \tag{1.3}$$

Considering the vehicle attitudes are small enough such that the small angle assumption holds, then (1.3) can be simplified to the following

$$\theta_y = \theta_{yss} - \omega_z \frac{v_y}{g}$$
$$\theta_x = \theta_{xss} - \frac{\dot{v}_y}{g} \tag{1.4}$$

Further, using a small angle assumption to the third equation of Equation (1.1), the following relationship is true

$$\dot{\theta}_x = \omega_x + \dot{\theta}_y \tan(\theta_y)\tan(\theta_x) + \omega_z \tan(\theta_y)\sec(\theta_x)$$
$$\approx \omega_x + [\dot{\theta}_{yss} - \dot{\omega}_z \frac{v_y}{g} - \omega_z \frac{\dot{v}_y}{g}]\theta_{yss}\theta_{xss} + \omega_z\theta_y \tag{1.5}$$
$$\approx \omega_x + \omega_z\theta_y$$

Define the following as the slide index

$$SI = (\dot{\theta}_{xss} - \omega_x - \omega_z\theta_{yss})g \tag{1.6}$$

then the lateral velocity satisfies the following single differential equation at any time instant t

$$\ddot{v}_y(t)+\omega_z(t)^2 v_y(t)=SI(t) \tag{1.7}$$

Notice that SI characterize the strength of the sliding of the vehicle by using the known or the calculated and the measured variables. If $SI=0$, (1.7) leads to

$$\ddot{v}_y(t)+\omega_z(t)^2 v_y(t)=0$$

and the only solution v_y satisfying the above is $v_y=0$. Therefore, a small magnitude of SI implies a small amount of lateral velocity, hence small sliding of the vehicle; a large magnitude of SI implies a large magnitude of lateral velocity, hence large sliding of the vehicle. This is also the reason this quantity is called a sliding index. Based on the above discussion, the determination of the lateral velocity might be conducted as in the following for some threshold s of the sliding index

if $|SI(k)|\leq s$
{
vehicle lateral velocity is negligible.
}
else if $|SI(k)|> s$
{
vehicle lateral velocity is significant
quantitatively computing vehicle lateral velocity
}

Although Equation (1.7) could be used to solve for lateral velocity in real-time using Tyler expansion plus difference equations and numerical integration, such an approach is not robust and reliable for real time implementation due to potential uncontrollable

accumulative error and low frequency drifting of the integration.

If the vehicle yaw rate $\omega_z(t)$ is kept constant, for instance $\omega_z(t)=\Omega$, with time elapse, the lateral velocity could be directly solved in closed form expression as

$$v_y(t)=\frac{1}{\Omega}[-\cos(\Omega t)\int_0^t SI(\tau)\sin(\Omega\tau)d\tau+\sin(\Omega t)\int_0^t SI(\tau)\cos(\Omega\tau)d\tau]$$
$$\dot{v}_y(t)=\sin(\Omega t)\int_0^t SI(\tau)\sin(\Omega\tau)d\tau+\cos(\Omega t)\int_0^t SI(\tau)\cos(\Omega\tau)d\tau \quad (1.8)$$

Since the vehicle yaw rate is usually time-varying, hence the above closed form solution in (1.8) might not be useful. However, if we replace the constant Ω by the integration of the yaw rate as in the following

$$\Omega_t=\int_0^t \omega_z(\tau)d\tau \quad (1.9)$$

then the lateral velocity and its derivative can be expressed as in the following

$$v_y(t)=\frac{1}{\omega_z(t)}[-\cos(\Omega_t)\int_0^t SI(\tau)\sin(\Omega_\tau)d\tau+\sin(\Omega_t)\int_0^t SI(\tau)\cos(\Omega_\tau)d\tau]$$
$$\dot{v}_y(t)=\sin(\Omega_t)\int_0^t SI(\tau)\sin(\Omega_\tau)d\tau+\cos(\Omega_t)\int_0^t SI(\tau)\cos(\Omega_\tau)d\tau$$

(1.10)

That is, the lateral acceleration is related to the projection of the sliding index using the yaw angle of the vehicle.

In order to verify that the solution documented in Equation (1.10) does obey the linear time

varying differential Equation (1.7), the time derivative for $\dot{v}_y(t)$ is found. Notice that $\dot{\Omega}_t = \omega_z(t)$, hence

$$\ddot{v}_y(t) = \frac{d\dot{v}_y(t)}{dt}$$
$$= \cos(\Omega_t)\dot{\Omega}_t \int_0^t SI(\tau)\sin(\Omega_\tau)d\tau - \sin(\Omega_t)\dot{\Omega}_t \int_0^t SI(\tau)\cos(\Omega_\tau)d\tau$$
$$+ \sin(\Omega_t)SI(t)\sin(\Omega_t) + \cos(\Omega_t)SI(t)\cos(\Omega_t)$$
$$= -\omega_z(t)^2 v_y(t) + SI(t)$$

which implies that the solution expressed in Equation (1.10) does satisfy Equation (1.7).

Since the lateral velocity $v_y(t)$ and its derivative $\dot{v}_y(t)$ described in Equation (1.10) come from a kinematic equation, they are accurate regardless of the vehicle's driving condition, the road condition, the road surface condition and the vehicle platform as soon as the sensors are mounted on the center of gravity of the car body and the relative attitudes of the vehicle with respect to the average road surface are accurately calculated. Another advantage of the above computation of the lateral velocity is that it does not explicitly involve the road bank, road slope and vehicle attitude information, and the influence of all those variables is reflected by the relationship shown in the differential Equation (1.7) through the sliding index.

A numerical implementation of the closed-form solution in Equation (1.10) is performed to allow the implementation in a useful manner. The yaw angle of the vehicle car body Ω_t, as defined in Equation (1.9), can be computed using the following pure integration scheme

$$\Omega_{k+1} = \Omega_k + \omega_{z_{k+1}} \Delta T \qquad (1.11)$$

where ΔT is the sampling time of the control system, Ω_{k+1} and $\omega_{z_{k+1}}$ are the values of the yaw angle and the yaw rate sensor at time instant $t=(k+1)\Delta T$. Because of the potential drift problem, Equation (1.11) may not be close to the actual yaw angle. However, Ω_{k+1} appears only in sine and cosine functions, drifting may be eliminated by using the following congruent mod operation

$$\Omega_{g_{k+1}} = \Omega_{k+1} - 2\pi floor(\frac{\Omega_{k+1}}{2\pi}) \qquad (1.12)$$

Combining (1.11) and (1.12), the following iterative scheme can be used to compute the congruent-mod yaw angle

$$\Omega_k = \Omega_k - 2\pi floor(\frac{\Omega_k}{2\pi})$$
$$\Omega_{k+1} = \Omega_k + \omega_{z_{k+1}} \Delta T$$

Notice that $\Omega_{g_{k+1}}$ calculated in (1.12) falls always within 0 and 2π. The $floor(\bullet)$ is a function which is the largest integer bounded by the real number $\bullet$. That is, $floor(\frac{\Omega(k+1)}{2\pi})$ always removes out of the portion that are integer times of 2π from $\Omega(k+1)$, and it outputs a quantity with value falling in between 0 and 2π. This function is common in "C" programming language. The following intermediate variables may be computed.

The projections of the sliding index SI along the yaw angle directions can now be computed based on the computed $\Omega_{g_{k+1}}$. Define

$$SI\sin\text{int} = \int_0^t SI(\tau)\sin(\Omega_\tau)d\tau$$

$$SI\cos\text{int} = \int_0^t SI(\tau)\cos(\Omega_\tau)d\tau$$

then the numerical computation of them using the following anti-drift-integration filter

$$T_{AID}(z^{-1}) = \frac{d(1-z^{-2})}{1-c_1 z^{-1}+c_2 z^{-2}}$$

can be obtained as the following

$$\begin{aligned} SI\sin\text{int}_{k+1} &= c_1 SI\sin\text{int}_k - c_2 SI\sin\text{int}_{k-1} \\ &\quad + d[SI_{k+1}\sin(\Omega_{g_{k+1}}) - SI_{k-1}\sin(\Omega_{g_{k-1}})] \\ SI\sin\text{int}_{k+1} &= c_1 SI\sin\text{int}_k - c_2 SI\sin\text{int}_{k-1} \\ &\quad + d[SI_{k+1}\cos(\Omega_{g_{k+1}}) - SI_{k-1}\cos(\Omega_{g_{k-1}})] \end{aligned} \tag{1.13}$$

Using the numerical scheme shown in Equation (1.13), the following computation for the lateral velocity and its derivative based upon the sliding index along the yaw angle direction is shown as

$$\begin{aligned} v_{y_{k+1}} &= \frac{1}{\omega_{z_{k+1}}}[-\cos(\Omega_{g_{k+1}})SI\sin\text{int}_{k+1} + \sin(\Omega_{g_{k+1}})SI\cos\text{int}_{k+1} \\ \dot{v}_{y_{k+1}} &= \sin(\Omega_{g_{k+1}})SI\sin\text{int}_{k+1} + \cos(\Omega_{g_{k+1}})SI\cos\text{int}_{k+1} \end{aligned} \tag{1.14}$$

As mentioned above, a control signal may then be developed based on the lateral velocity and perhaps the lateral velocity derivative found in Equation (1.14). For example, a roll or a yaw stability control system may derive the control signal therefrom. Of course, multiple systems may simultaneously use the lateral velocity and/or the lateral velocity derivative in its computations.

Referring now to Figure 5, a summary flow chart illustrating the process is illustrated. The

various sensors are read in step 70. In the following examples the yaw rate sensor 28, the roll rate sensor 34, the speed sensor 20, lateral acceleration sensor 32, and longitudinal acceleration sensor 36 are used. A steady state pitch and roll angle in step 72 is obtained from Equation (1.2) above. A sliding index is determined in step 74 which corresponds to Equation (1.6) above. The sliding index is projected along the yaw angle direction in step 76. The yaw angle projection is set forth in Equation (1.13).

Based upon the projection of the sliding index along the yaw angle direction, step 78 determines a linear time varying differential equation as a function of the sliding index projection. In step 80, the lateral velocity and the velocity derivative are obtained. In step 82, a control system such as a safety system is controlled in response to the lateral velocity and/or the lateral velocity derivative.

Claims

1. An apparatus for determining lateral velocity of a motor vehicle comprising a vehicle speed sensor for generating a vehicle speed signal, a roll rate sensor for generating a roll rate signal, a yaw rate sensor for generating a yaw rate signal, a lateral acceleration sensor for generating a lateral acceleration signal, a longitudinal acceleration sensor for generating a longitudinal acceleration signal and a controller coupled to the sensors for determining a steady state pitch angle and a steady state roll angle as a function of the lateral acceleration signal, the longitudinal acceleration signal, the yaw rate signal, and the vehicle speed signal, determining a sliding index as a function of the steady state pitch angle, the steady state roll angle and the roll rate signal, and determining a lateral velocity as a function of the sliding index.

2. An apparatus as claimed in claim 1 further comprising a safety system coupled to the controller, the safety system operating in response to the lateral velocity.

3. An apparatus as claimed in claim 2 wherein the safety system comprises a yaw control system.

4. An apparatus as claimed in claim 2 wherein the safety system comprises a roll stability control system.

5. An apparatus as claimed in any of claims 1 to 4 wherein the controller determines a lateral velocity and a lateral velocity derivative as a function of the sliding index.

6. A method of controlling a vehicle comprising measuring a vehicle speed, measuring a roll rate of the vehicle, measuring a yaw rate of the vehicle, measuring a

lateral acceleration of the vehicle, measuring a longitudinal acceleration of the vehicle, determining a lateral velocity as a function of the longitudinal acceleration, the vehicle speed, the lateral acceleration, the yaw rate and the roll rate and controlling a safety system in response to the lateral velocity.

7. A method as claimed in claim 6 wherein the method further comprises determining a steady state pitch angle as a function of the longitudinal acceleration and the vehicle speed.

8. A method as claimed in claim 6 or in claim 7 wherein the method further comprises determining a steady state roll angle as a function of the lateral acceleration, the yaw rate, and the vehicle speed.

9. A method as claimed in any of claims 6 to 8 wherein the method further comprises determining a sliding index as a function of the steady state pitch angle, the steady state roll angle and the roll rate.

10. A method as claimed in claim 9 wherein the method further comprises determining a lateral velocity derivative as a function of the sliding index.

11. A method as claimed in any of claims 6 to 10 wherein the safety system comprises a yaw control system.

12. A method as claimed in any of claims 6 to 10 wherein the safety system comprises a rollover control system.

13. A method as claimed in claim 9 further comprising generating a differential equation obeyed by the lateral velocity and its derivative by using the sliding index.

14. A method as claimed in claim 13 wherein the differential equation is derived by projecting the sliding index along a yaw angle direction.

15. A method as claimed in claim 14 wherein the step of projecting the sliding index along the yaw angle directions is accomplished using an anti-drift-integration filter.

16. A method as claimed in any of claims 6 to 15 further comprising computing yaw angle through pure integration and 2π congruent mod operation, such that the accumulated integration error of the real signal is eliminated.

17. An apparatus for determining lateral velocity of a motor vehicle substantially as described herein with reference to the accompanying drawing.

18. A method of controlling a vehicle substantially as described herein with reference to the accompanying drawing.

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Claims searched: All

Examiner: Jacob Collins
Date of search: 19 August 2003

Patents Act 1977 : Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance	
Y	6, 11 & 12	GB 2280651 A	(DAIMLER-BENZ)
Y	6, 11 & 12	EP 1110834 A2	(FORD)
Y	6, 11 & 12	US 5408411	(NAKAMURA ET AL)
Y	6, 11 & 12	EP 0827852 A2	(FORD)
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The following online and other databases have been used in the preparation of this search report:

WPI, EPODOC, JAPIO